Spatial Reuse and Random Data Hopping in Multihop Ad-hoc Networks

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Hrishikesh Venkataraman
School of Engineering and Science,
Jacobs University Bremen, Germany
h.venkataraman@jacobs-university.de

Sinan Sinanović and Harald Haas
Institute for Digital Communications,
University of Edinburgh, UK
{s.sinanovic, h.haas}@ed.ac.uk

***Abstract*— Spatial reuse TDMA (time division multiple access) in multihop *ad hoc* network is a subject of intense research interest for next generation wireless systems. In this paper, the selection of concurrent communication pairs, that utilize the same resources, is formulated as a non-linear mixed integer programming problem. However, it has been found that the solution to this non-linear programming problem is NP-hard. Recently, a random data hopping (RDH) technique applied over a time slot partitioned system has been proposed by the authors as a novel heuristic algorithm. This random data hopping scheme is further studied in this paper for different values of traffic loads, and its performance is evaluated under realistic propagation conditions. It has been found that the variation of the system throughput with the traffic load follows a concave function, and it reaches its peak when the traffic load is around 30%.**

***Keywords*: Spatial reuse TDMA, interference avoidance model, random data hopping.**

I. Introduction

One of the most challenging problems in multihop *ad hoc* networks is to guarantee a certain quality of service (QoS). This problem is usually considered in the medium access control (MAC) layer. Traditionally, MAC protocols for *ad hoc* networks are based on dynamic access methods such as carrier sense multiple access (CSMA), e.g., the IEEE 802.11 standard. Although efforts have been made to guarantee QoS in CSMA based MAC protocols, such methods are inherently inappropriate for providing QoS guarantees [1]. The main reason for this inadequacy is the hidden node/ exposed node problem, and exponential back-off schemes, which results in large delays in multihop wireless networks [2]. One of the most important QoS in many applications is delay guarantee, i.e., the upper bound on the time it takes to transmit a message from the source to destination. This is useful when transmitting delay sensitive traffic such as voice or video. One approach where delay bounds can be guaranteed is time division multiple access (TDMA). Unfortunately, this is usually inefficient in sparsely connected networks. However, due to multihop properties, the time slots (TSs) can often be shared by more than one user without conflicts. Therefore, the given resources can be spatially reused in any TS of a TDMA system, in order to increase the network capacity. The idea is to let the spatially separated radio terminals reuse the same TSs when the resulting interference is not severe (exactly how much interference could be tolerated by a receiver, so that it can still detect its desired signal, would depend on the carrier signal strength and on the system specifications). Such a protocol is called spatial reuse TDMA, or STDMA. The gain from spatial reuse must, however, outweigh the increased interference arising from the additional number of transmissions required between the source and destination nodes in the multihop design, in order to achieve an improvement in the capacity.

Spatial reuse in TDMA based multihop packet radio networks was first studied more than two decades back in [3], and was introduced as a collision free access scheme for multihop *ad hoc* networks. The concept of a spatial reuse channel access schedule for multihop radio networks was formalized by Nelson and Kleinrock [4]. A STDMA scheduler describes the transmission rights for each TS. In the literature, various algorithms for generating reuse schedules have been proposed. Centralized algorithms [5], [6] as well as distributed algorithms [3], [7] have been proposed for multihop *ad hoc* networks. Most of the early work in the literature have in common that the reuse schedule is designed from a graph-model of the network [8], wherein the radio terminals that are located beyond a certain distance could communicate simultaneously. The graph-based scheduling technique is therefore based on the same principle as the interference-avoidance *Protocol Model*. Recently, Sinanović *et. al.* [9] derived the conditions when the spatial reuse of resources would result in higher spectral efficiency for a simple 2-link *ad hoc* network. Zander [10] proposed an alternative interference model where the signal-to-interference ratio (SIR) is used to describe the interferences in the network. The schedule was defined to be conflict-free if the SIR does not fall below a certain threshold. However, the main disadvantage of such an SIR-based STDMA scheduling is the increased network complexity and the control overhead, as the interference and the SIR has to be calculated at the receiver of every potential communication pair. Hence, in this paper, the multihop network is analyzed under the interference-avoidance *Protocol Model*. There are two significant contributions of this paper. Firstly, a mathematical representation of the system complexity is provided for a spatial-reuse multihop wireless network. Secondly, the random data hopping technique introduced in [11] has been further studied in this paper for different system traffic load and the variation in the network capacity is computed.

The paper is organized as follows: In section II, the multihop wireless network is described in detail and the optimum system capacity of the spatial-reuse multihop design is presented as a non-linear integer programming problem. The random data hopping technique and the expression for system capacity is explained in section III. The simulation results are provided in section IV, and finally, the conclusion is provided in section V.

II. System Description

A. Multihop Ad hoc Network

The multihop *ad hoc* network is modeled to be deployed in a square-shaped coverage area, Z, with a side length, s. The mobile stations (MSs) are assumed to be uniformly distributed in the given coverage area. A restrictive version of the *Protocol Model* is considered in this paper, in order to suppress the interference arising from simultaneous communication of several transceiving pairs. As per this model, a circular exclusion region is defined around the receiver of every communication pair [12]. All other concurrently communicating transmission pairs lie outside this exclusion region. The exclusion region of the concurrently communicating pairs do not overlap with each other. This results in several non-overlapping exclusion region circles in the coverage area. The radius of this exclusion region circle, r_c, is a function of the transmission distance, d_c, between the communicating pair, and is given by, $r_c = d_c(1+\Delta)$, where $\Delta \geq 0$ is the spatial protection margin defined around the receiver. It is shown in [13] that a maximum throughput is realized when the value of Δ is close to 1.0. Hence, in this paper, a constant spatial protection margin, $\Delta = 1.0$, is considered for all transmission pairs. However, the transmission distance of all the communication pairs are different. Therefore, the radii of all the exclusion region circles are different, which results in non-overlapping of unequal exclusion region circles in the coverage area. On account of this, the 'optimal throughput calculation problem' for a multihop *ad hoc* network with a finite coverage area is now transformed into an 'optimal unequal circle packing problem'.

B. System Complexity

For any TS, the instantaneous number of simultaneously communicating pairs in the system, n_t, is a random variable that depends on the location of the communicating pairs. The upper bound on the number of simultaneously communicating pairs for any TS, L_M, depends on the area of the coverage area, and more significantly, on the radii of the exclusion region circles. In a practical scenario, the condition for the number of simultaneously communicating pairs for any TS is $1 \leq n_t \leq L_M$. If the radii of the n_t circles are given by $r_1, r_2, ..., r_{n_t}$, and if x_i and y_i indicate the X and Y co-ordinates of the circle i, $i \in \{1,2,...,n_t\}$, then the optimum packing problem of unequal circles can be formulated as follows:

$$\max(n_t) \quad \text{subject to}$$

$$r_i \leq x_i \leq s - r_i \quad \text{for} \quad i \in \{1,2,...,n_t\} \quad (1)$$

$$r_i \leq y_i \leq s - r_i \quad \text{for} \quad i \in \{1,2,...,n_t\} \quad (2)$$

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad \geq \quad r_i + r_j \;\; \text{for } i \neq j \quad (3)$$

$$0 < r_i \leq s/2 \quad (4)$$

$$0 < s < +\infty \quad (5)$$

It should be noted that the conditions (1) and (2) ensure that none of any part of each circle is outside the coverage area whereas condition (3) ensures that there is no overlapping of exclusion region circles. There are usually many different packing configurations which give the same objective function value, and the feasible solutions differ only in the pattern in which the circles are placed [14]. This formulation is a formidable non-linear mixed integer mathematical problem. In fact, it is shown in [15] that for this class of packing problem, it is not only NP-hard to determine the optimal packing, but also, it is prohibitively complex to approximate the optimal packing problem, even for small values of n_t. In addition, in the multihop network design, the maximum packing problem is further compounded by the fact that x_i and y_i (the center of the exclusion range circles) cannot be in general freely chosen, but rather depends on the location of mobile/relays. However, this additional condition could be relaxed in the analysis, by the fact that the radius, r_i, of the exclusion region circle could be varied by appropriately selecting the peer node.

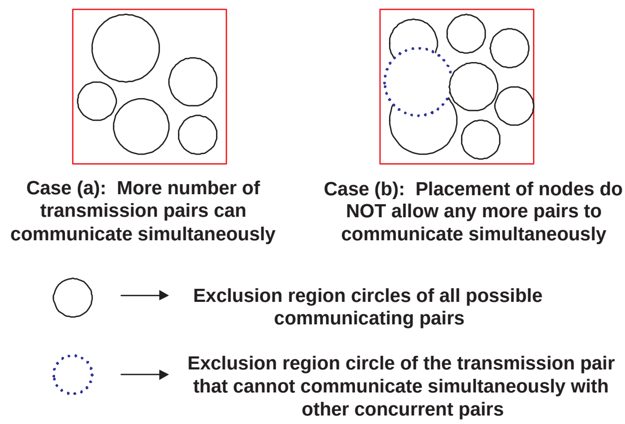

Fig. 1. Packing of unequal sized non-overlapping circles in the square-shaped coverage area

III. Random Data Hopping Technique

In a distributed multihop wireless network, the number of transceiving pairs that can communicate in a given coverage area at any time instant is a function of the position of selected nodes in the system. Fig. 1 (a-b) shows two cases in a spatial-reuse multihop *ad hoc* network, where the exclusion region circles are distributed within the bounded coverage area. Case (a) represents a scenario where more number of pairs could communicate simultaneously, but there are no more transmission pairs for communication. In case (b), the placement of the communicating pair of nodes are such that no more nodes could transmit data in the particular time instant. However, it can be seen that an efficient placement of nodes results in an increased number of concurrently communicating pairs for any time instant. In this technique, each time slot is first partitioned into several mini TSs and the mini TS over which the particular transmission pair communicates is randomly varied [11]. Hence, the number of concurrent communication pairs over each mini TS gets altered randomly. This is the underlying principle behind the random data hopping technique.

A. Multihop Network Model

In a spatial reuse multihop network model, the power at the receiver of the i^{th} transceiver pair, separated by a distance, d_{c_i}, is found from a generic pathloss model as:

$$P_R = P_T - (k_1 + 10\alpha \log_{10}(d_{c_i}))\ \mathrm{dB} \tag{6}$$

where P_T is the transmit power, α is the pathloss exponent and k_1 is a propagation constant. A constant transmit power is assumed for all the nodes in the system. For each of the n_t simultaneously communicating pairs at any time slot, t, the remaining $n_t - 1$ simultaneous communicating pairs act as interferers. Therefore, the carrier-to-interference ratio, γ_{it}, of the i^{th} communicating pair at t^{th} TS is given by

$$\gamma_{it} = \frac{10^{P_T/10}\ \ 10^{-\left(k_1+10\alpha\log_{10}(d_{\mathrm{c_i}})\right)/10}}{\sum_{j=1,j\neq i}^{n_t} 10^{P_T/10}\ \ 10^{-\left(k_1+10\alpha\log_{10}(d_{\mathrm{int}_{ij}})\right)/10}} \tag{7}$$

which simplifies to

$$\gamma_{it} = \frac{{d_c}^{-\alpha}}{\sum_{j=1,j\neq i}^{n_t} {d_{\mathrm{int}_{ij}}}^{-\alpha}} \tag{8}$$

where $d_{\mathrm{int}_{ij}}$ is the distance between the receiver of the i^{th} communicating pair and the transmitter of the j^{th} communicating pair. The distance between a desired receiver and an unintentional transmitting entity is given by $d_{\mathrm{int}_{ij}} \geq (1+\Delta)d_c$. The expression for γ_{it} can be lower bounded by assuming that all the interfering nodes are at the circumference of the exclusion region itself. In this case, all the interfering transmitters would be at the closest possible distance from the intended receiver. Hence, this would model the worst-case interference scenario. For such a scenario, the distance of all the transmitting interferers from the receiver of the i^{th} communicating pair would be given by $d_{\mathrm{int}_{ij}} = (1+\Delta)d_c$. The carrier-to-interference ratio, γ_{it}, in eqn. (8), can therefore be lower bounded as follows:

$$\gamma_{it} \geq \frac{(1+\Delta)^{\alpha}}{n_t - 1}\ \forall\ i \in \{1, 2, ..., n_t\} \tag{9}$$

The average system capacity for the wireless network is calculated from the expected values of γ_{it} and n_t.

B. Calculation of System Capacity

The Shannon equation for system capacity is used to derive the equation for aggregate system capacity. For a continuous transmission by a communication pair, the Shannon capacity of the system is given by:

$$C_s = \log_2(1+\gamma)\ \ \text{bps/Hz} \tag{10}$$

where C_s indicates the Shannon capacity of the communication link, and γ is the carrier-to-interference ratio, at the receiver of the communication link. However, the performance measure for the multihop *ad hoc* network that is considered in this research work is the aggregate system capacity of the network.

In a multihop system, there are several communication pairs per link. Each of these pairs would communicate for only one of the T TSs. Hence, each of the pairs would contribute to the capacity for only one of the T TSs. In addition, since the TDMA frame has T TSs, the calculation for system capacity is performed for all T TSs. Apart from that, in general, n_t is different for each TS. Hence, while calculating the aggregate system capacity, the capacity has to be calculated for each of the n_t concurrently communicating pairs.

It is to be noted that the total area occupied by the exclusion regions of all the communicating pairs for any time instant, t, is given by

$$A = \sum_{i=1}^{n_t} B_i \tag{11}$$

Packing of non-overlapping unequal circles, however close, would always result in some unoccupied area between the exclusion range circles. Hence, the sum of the area of the exclusion range circles, A, given by eqn. (11) would always be less than the coverage area, Z, considered in the system, i.e., $A \leq Z$. It should be noted that scaling by the term Z is more appropriate than scaling by the factor, A. Hence, in order to calculate the aggregate system capacity for a given coverage area, the equation for the system capacity is scaled by the factor, Z.

The equation for aggregate system capacity is written as follows:

$$C = \frac{1}{ZT}\sum_{t=1}^{T}\sum_{i=1}^{n_t}\log_2(\gamma_{it}+1)\ \ \text{bps/Hz/km}^2 \tag{12}$$

A unit coverage area is considered throughout in the system design for the multihop *ad hoc* network. Also, in the calculation of eqn. (12), it is assumed that all the nodes have sufficiently long buffer. Hence, all the pairs of a communicating link would communicate, either in the given time frame or in subsequent time frames. Therefore, all the communicating pairs contribute to the system capacity.

C. Effect of Log-Normal Shadowing

In order to study the performance of the random data hopping technique under realistic pathloss conditions, a lognormal shadowing with a standard deviation of 4 dB is considered. In the presence of lognormal shadowing, the received power, P_R, and the carrier-to-interference ratio, C/I, given in eqn. (6) and eqn. (8) would be modified as follows:

$$P_R = P_T - (k_1 + 10\alpha \log_{10}(d_c)) + \zeta \ \text{dB} \tag{13}$$

and

$$\gamma_{it} = \frac{10^{P_T/10} \ 10^{-(k_1+10\alpha\log_{10}(d_c)+\zeta_i)/10}}{\sum_{j=1,j\neq i}^{n_t} 10^{P_T/10} \ 10^{-\left(k_1+10\alpha\log_{10}(d_{\text{int}_{ij}})+\zeta_j\right)/10}} \tag{14}$$

which simplifies to

$$\gamma_{it} = \frac{{d_c}^{-\alpha}/\zeta_i'}{\sum_{j=1,j\neq i}^{n_t}\left(\frac{{d_{\text{int}_{ij}}}^{-\alpha}}{\zeta_j'}\right)} \tag{15}$$

where ζ_i' and ζ_j' are the absolute values of the shadowing term of the transmission path and the interfering path respectively, and is given by, $\zeta' = 10^{0.1\zeta}$. The equation for system capacity, C, remains the same as given in eqn. (12).

IV. Simulation Results

A deeper insight into the system model is obtained by assuming a unit coverage area of 1km^2 with 500 uniformly distributed MSs across the coverage area. The MS located closest to the transmitter and in the direction of the final destination node is always selected as the relay node. For an exclusion range ratio of *two* (i.e., $\Delta = 1.0$), the area of the exclusion region circle is $B = 4\pi{d_c}^2$. A fixed TDMA frame of duration 100 ms is considered in the system. The time slot granularity is varied from 5 TSs per frame, each with a duration of 20 ms to a maximum of 100 TSs per frame each with a duration of 1 ms. It is assumed in this research work that a single packet has to be transmitted for a minimum duration of 1 ms. Hence, for 100 TSs in the frame, the time frame duration is taken as 100 ms. In addition, the number of MSs that have data to transmit determine the traffic demand. A 100% traffic load indicates that half the total number of MSs in the system act as source nodes, and the other half act as destination nodes. Hence, for a system with 500 nodes, a 100% traffic load would indicate that there are 250 communication links. The source node communicates to its intended receiver in multiple hops, wherein the MSs located between the source and destination act as relays. These relay MSs may have their own data to transmit depending on their traffic pattern. It should be noted that at any node, the data is transmitted to the immediate receiver after employing the random data hopping technique. The average system capacity is calculated using eqn. (12). The simulation result plotted in Fig. 2 illustrates that due to TS partitioning, with an increase in the number of TSs per frame from 5 to 100, the average system capacity shows a significant improvement. This is because of the following: The number of TSs per frame is increased by partitioning the TSs. For a higher number of TS(s) per frame, the random data hopping technique produces an inherent randomness in the placement of nodes. This results in an increased number of occasions when a high number of communicating pairs could be established in any TS. This increase results from a better spatial reuse for the given TS, and hence, results in an increase in the average system throughput.

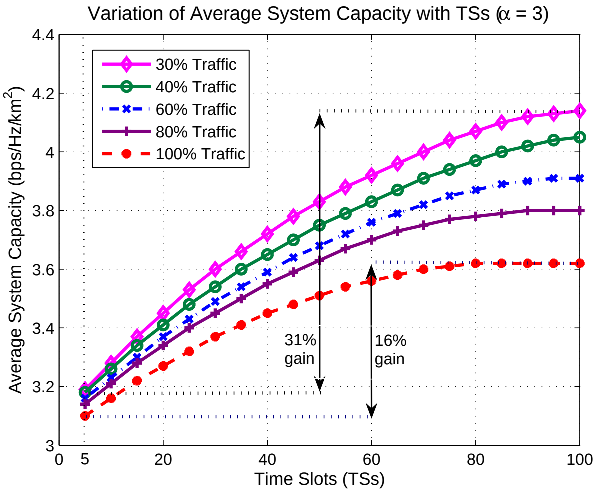

Fig. 2. Simulation result of throughput variation for different TSs under different traffic loads

The simulation results also show that for low traffic load, the obtainable system capacity is higher than the case for high traffic load. This is because, for less traffic, the total interference experienced by any communicating receiver is less as compared to the high traffic scenario. Hence, the C/I experienced at any receiver is higher. This results in an increase in the average system capacity for a multihop network with a low traffic load, compared to a multihop design with a high traffic load. Fig. 2 shows that for a system with a 100% traffic load, a maximum increase in the average system capacity that could be obtained by employing the random data hopping technique would be around 16%. When the traffic load is less, the improvement obtained by the random data hopping scheme is higher. For e.g., at 30% traffic, a increase of around 31% is observed at 100 TSs per time frame. It can also be observed from Fig. 2 that for high traffic load (80% and 100% traffic in Fig. 2), the system capacity saturates at around 100 TSs per frame, compared to low traffic load (30% and 40% traffic) where the throughput does not saturate at even 100 TSs per frame. The simulation results for the lognormal shadowing scenario are plotted in Fig. 4. It can be observed that, even in the presence of lognormal component, the RDH technique shows an improvement in the performance. For 30% traffic load, a maximum improvement of 21% is observed as compared to the 31% improvement in the absence of log-normal component. This is because, the interference experienced by any receiver node due to an interfering transmitter located at a much far-off distance could be higher due to the lognormal component, which in turn deteriorates the performance of the RDH algorithm.

At this stage, it should be mentioned that an intelligent routing technique in the multihop *ad hoc* network might provide still better result. However, this paper does not focus on the benefits of employing smart routing techniques. In order to further study the effect of traffic load, the variation of system capacity with the traffic load is observed for different values of TS partitions and is shown in Fig. 3. It can be seen

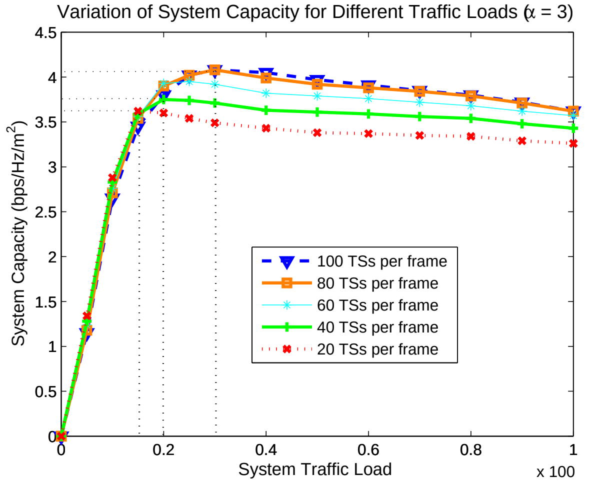

Fig. 3. Variation of system capacity with traffic loads for different TSs

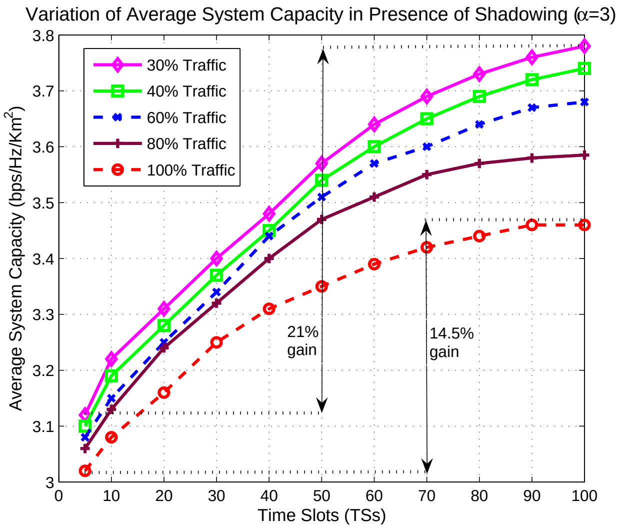

Fig. 4. Variation of system capacity with traffic loads for different TSs in the presence of log-normal shadowing

that, irrespective of the number of TSs per frame, the variation of system capacity observes a similar pattern. Initially, the capacity increases with increasing traffic and attains a peak for a certain value of traffic load (around 25% - 30%), after which the system capacity decreases. This indicates that there exists an optimum value of traffic load (i.e., an optimum ratio between the communicating nodes and the relay nodes where the system capacity is maximized).

V. Conclusions

In a distributed multihop network with no central controller, it is an NP-hard problem to find an optimum allocation scheme that would spatially reuse the resources, and thereby, maximize the system capacity. A simple mechanism that has been found to efficiently assign the radio resources is the random data hopping algorithm. In this technique, the TS granularity of the TDMA frame is first increased by reducing the duration of each TS. A random data hopping scheme, is then implemented, whereby, the TS over which the transmission pair communicates is varied randomly. In an important result, it has been shown through computer simulations that an increase in the TS granularity, combined with the random data hopping technique provides a significant increase in the performance, which varies with the traffic load of the system (31% gain for a traffc load of 30%, as compared to 16% gain for a traffic load of 100%). However, irresepective of the number of TS partitioning, the peak gain of the random hopping method is attained for a traffic load varying between 25%-30%. This provides an important direction for future research - finding an analytical expression for the optimum traffic load that would maximize the performance of the random data hopping algorithm, similar to the ALOHA system.

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